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Effects of Drilling Mud on the Reef-Building Coral 'Montastrea annularis'

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Effects of Drilling Mud on the Reef-Building Coral *Montastrea annularis*

R. E. Dodge

Nova University Oceanographic Center; 8000 North Ocean Drive, Dania, Florida 33004, USA

Abstract

The skeletal extension and corallite shape of individuals of the Caribbean and Atlantic reef-building coral *Montastrea annularis* (Ellis and Solander) were measured after more than six weeks' continuous flow-through exposure in laboratory aquaria to treatments of 0, 1, 10 and 100-ppm ($\mu l\ l^{-1}$) drilling mud. Linear increase of the skeleton (extension rate) and fossa length were significantly depressed in the 100-ppm treatment. Chronic exposure to 100-ppm drilling mud impairs coral skeletal growth rate and possibly interferes with sediment rejection capability by lowering calical relief.

Introduction

Drilling fluids or muds are highly specialized materials necessary for the drilling of offshore wells. "... These fluids may consist of pH and ion-control substances ($NaOH_3$, $NaHCO_3$), gelling and suspension agents (clay minerals and acryllic polymers), deflocculants and filtration control substances (ferrochrome lignosulfonate, sodium acid pyrophosphate), fuel oil, defoaming agents (aluminum stearate), and weighting agents (barite)." (Trefrey *et al.*, 1981a). Barium (in the form of $BaSO_4$) is the main ingredient for weighting material and can be as much as 15% of the drilling fluid mass. Ferrochrome lignosulfonate accounts for high Cr concentrations in the mud. Other trace elements such as Pb and Zn are potential contaminants (Trefrey *et al.*, 1981b).

A drilling operation may last for several months and many tons of drilling mud can be introduced into the marine environment gradually (e.g. during cuttings discharge where adhering mud washes off as cuttings settle to the bottom) and/or suddenly (e.g. during bulk discharge when large volumes of mud are dumped either to make room for new mud preparation or at the end of a drilling operation).

Drilling fluids in certain concentrations over various exposure periods are detrimental to reef coral. Slurries of drilling mud applied directly to the surface of three species (*Montastrea annularis*, *Diploria striogsa*, and *M. cavernosa*) are not rejected while individual components (barite, bentonite, and $CaCO_3$ sand) are cleared rapidly (Thompson and Bright, 1977). Thompson and Bright (1980) exposed seven species of coral to drilling mud. Several species were killed and six showed significant polyp retraction. A long-term laboratory study by Szmant-Froelich *et al.* (in press) indicated that calcification, respiration and gross photosynthesis were significantly depressed and that NO_3 uptake and NH_4^+ uptake were significantly elevated in *M. annularis*. Dodge and Szmant-Foelich (in press) reviewed drilling fluid effects on reef corals.

The goal of this study was to evaluate the effects of chronic (>6 wk) exposure of drilling mud on the skeletal extension or growth rate of reef-building corals. *Montastrea annularis* was chosen because of its use in other experiments, its availability, and its importance in reef ecology. This species has been termed the most important reef-forming coral of the Caribbean (Goreau, 1959).

Methods and Materials

Individuals of *Montastrea annularis* (Ellis and Solander) were collected from several columnar colonies in shallow water near Big Pine Key, Florida and airshipped within 24 h in oxygenated seawater to Stage I, a US Navy platform, 12 miles (ca 19 km) offshore of Panama City, Florida. Corals were allowed to adjust for several weeks in aquaria supplied with running seawater at ambient temperature (25 °C) and artificial light equivalent to collection depth (100 μEin $m^{-1}\ s^{-2}$) maintained on a 12 hL:12 hD cycle. On July 20, 1980 individuals for this study were stained for 24 h with alizarin red S (Lamberts, 1974) to establish an initial "time line" of color in the skeleton. These corals were randomly assigned to tanks having either a 0

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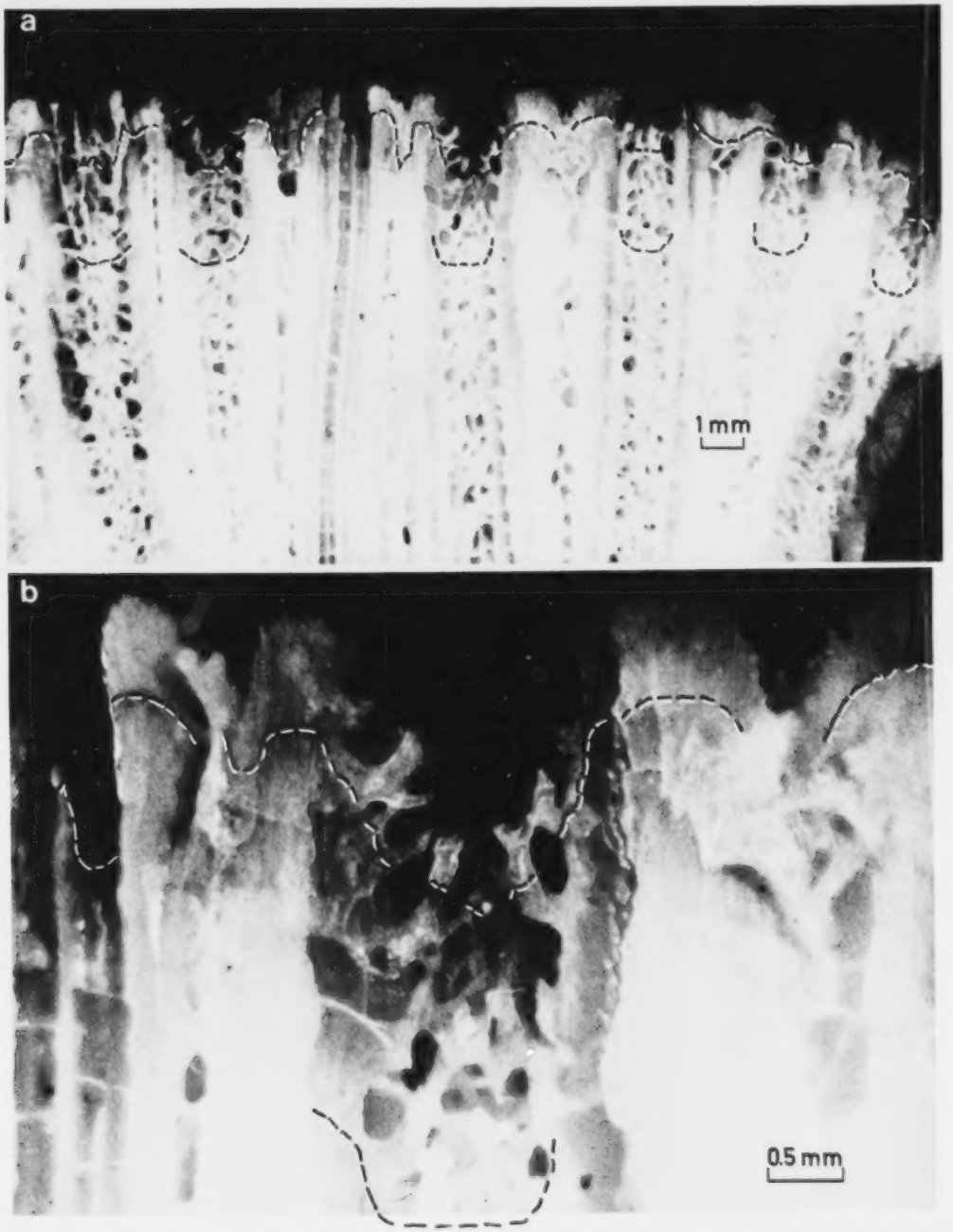

Fig. 1. *Montastrea annularis.* (a) Photograph showing appearance of embedded, cross-sectioned *M. annularis* coral individual after six week's exposure to drilling mud. The dashed black line indicates the position of the alizarin red stain line. (b) Enlargement of a corallite from (a) showing position of stain with dashed line

(control), 1, 10, or 100 ppm (μl l^{-1}) treatment of drilling mud (three stained corals/treatment).

Drilling fluids were obtained after use "downhole" from an exploratory land based drilling operation in Jay, Florida. The mud was a freshwater combination containing ferrochrome lignosulfonate (FCLS), barite, bentonite, and other additives. The specific composition of mud batches used varied because samples were taken at approximately one week intervals as drilling depth increased. Table 1 supplies information on dates of mud collection, dates of use in the experiment, trace metal concentrations, hydrocarbon concentrations (R. Shokes, personal com-

Table 1. Dates of collection and use and composition of experiment drill mud

Dates of Mud use in exp.	Exp. week #	Jay mud #	Mud collection date	Al %	Fe %	Ba %	Pb ppm	Cr ppm	Zn ppm	H_2O %	Tot. resolved aliphatics mg l^{-1}	Aromatics mg l^{-1}	# 2 fuel oil (diesel)
1980 July 21 – 27	1	2	7/ 9/80	8.47	3.82	4.53	25.4	84.4	196.0	80.9	36.5	1.13	< 60 $\mu g\ g^{-1}$
1980 July 28 – 8/2	2	3	7/11/80	8.49	3.70	3.70	30.7	132.0	200.0	82.6	39.4	–	< 60 $\mu g\ g^{-1}$
1980 Aug. 3 – 9	3	4	7/22/80	8.00	3.19	4.10	40.2	96.4	22.5	88.3	17.0	27.3	< 60 $\mu g\ g^{-1}$
1980 Aug. 10 – 18	4	5	7/29/80	6.54	2.58	9.29	41.7	201.0	271.0	82.6	1 320.0	380.0	4.8 mg g^{-1}
1980 Aug. 19 – 9/7	5,6	7	8/ 4/80	2.53	1.07	11.7	18.5	128.0	175.0	79.0	1 270.0	376.0	3.4 mg g^{-1}

Metal conc. in mass of metal/unit dry wt. of mud sample
Water content in weight of water/unit wet weight of mud sample
Hydrocarbon conc. in mass of component/unit volume mud fluid sample (aliphatics/aromatics)
Diesel conc. in mass/wet weight of mud sample

munication) and diesel oil concentration (T. Gilbert, personal communication) for each batch.

The drilling mud delivery system was composed of two separatory funnels containing whole drilling mud diluted with seawater: one at high concentration [440 ml mud (36.8 l water^{-1})] and one at low concentration [44 ml mud (36.8 l water^{-1})]. The diluted stock was continually stirred to maintain suspension and was further diluted to desired treatment levels by delivery to one of two multichannel peristaltic pumps which supplied slurries at rates of either 4.36 ml min^{-1} or 43.6 ml min^{-1} into the fresh seawater input (flow rate of 5.2 l min^{-1}) of appropriate aquaria. Mixing was maintained by a small dry well pump system within aquaria.

The continuous exposure treatments were maintained for 48 d. One stained coral exposed to the 100 ppm treatment died after 42 d and another after 46 d. Both were removed after their death. After exposure, all corals were processed for growth examination in reference to the alizarin red stain line. Specimens were sectioned using a diamond bit saw to obtain a medial slab several cm in thickness. Slabs were embedded under partial vacuum in clear polyester resin and resectioned after hardening. Each cut face was sequentially polished with labidary sand paper and grit to achieve a transparent surface suitable for low-power microscopic viewing.

Figure 1a, b shows the appearance of the skeleton of *Montastrea annularis* in embedded cross-section. Fig. 2 is a diagram of the cross-section in expanded scale showing a single corallite with locations and names of skeletal structures. The upper portion of the corallite, where the polyp resides, is the endotheca. This is composed of a basal plate (the dissepiment or endotheca base), septa extending outwards into and upwards from the endotheca cavity, more solid walls surrounding the endotheca (the septotheca), and a central portion (the columella). The columella is constructed of anastomosing projections of the septa at the center of the endotheca. The fossa is defined as the distance within the endotheca between the top of the columella and the tops of the septa. Endotheca length is defined as the distance between the tops of the septa and the base of the endotheca. Septa grow upwards in a continuous linear fashion while the endotheca base remains stationary until a new base is formed periodically and stepwise at a higher level (Wells, 1969).

Measurements were made with a microscope on individual corallites (from the central portion of the specimen) which were accurately cross-sectioned and which also provided a good resolution of the stain line. The number of corallites measured per coral ranged from four to eleven. By reference to the stain line it was possible to describe the growth of the corallites and the shape of the pre-experiment and post-experiment endotheca.

The parameters of growth measured were: increase in septa length (SI), increase in columella length (CI), and distance of upward movement of the endotheca base (EBI or endotheca base increase). The parameters of shape measured were: the length of the old and new fossa (OFL and NFL respectively), and the length of the old and new endotheca (OEL and NEL respectively). Fig. 2 shows the measurement parameters.

To test if any normalization was necessary, the mean pre-experiment endotheca lengths (OEL) were examined

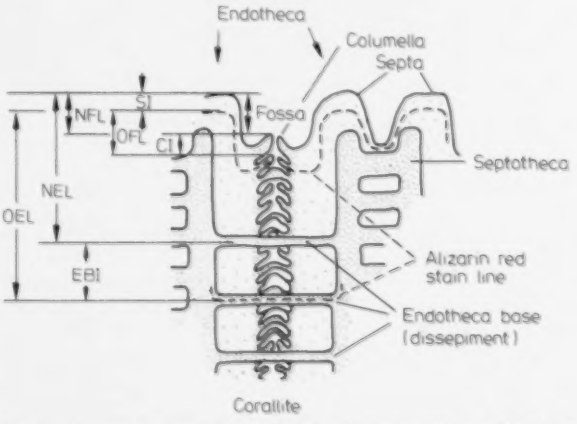

Fig. 2. *Montastrea annularis.* Sketch of cross-section of stained skeleton of *M. annularis* showing one corallite, various skeletal structures, and measurement parameters. SI = septa increase; CI = columella increase; EBI = endotheca base increase; NFL = new fossa lenght; OFL = old fossa length; NEL = new endotheca length; OEL = old endotheca length. The dashed line indicates the position of the alizarin red stain trace in the skeleton

by ANOVA and SNK tests (Zar, 1974). Results indicated that mean OEL of corallites in the 10-ppm treatment was significantly greater than in the 1 ppm treatment ($P < 0.01$) and clearly elevated relative to the mean for the control and 100 ppm treatment (see Fig. 4), probably due to the small sample size of both corals and corallites as well as the variability of corallite shape. Parameters of upward growth (SI, CI, EBI) were therefore normalized to their pre-experiment endotheca length (OEL) to supress pre-experimental variation for best comparison. Treatment means were then calculated as the average of these values.

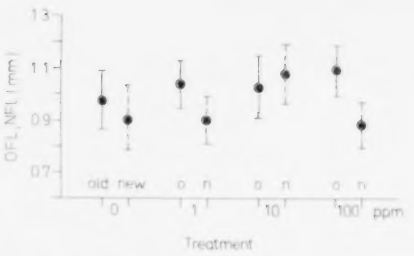

Fig. 3. *Montastrea annularis*. The effect of concentration of drilling mud on mean OFL (old fossa length) and mean NFL (new fossa length) of *M. annularis*. The error bar is the 95% confidence interval and is dashed for "new" values

Results

Parameters of Corallite Shape (Longitudinal Corallite Dimensions)

Averages for all corallites in each treatment of the shape parameters pre- and post-experiment fossa length (OFL and NFL) and pre- and post-experiment endotheca length (OEL and NEL) are included in Table 2.

Mean pre- and post-experiment fossa length for each treatment are illustrated in Fig. 3. Differences between the two mean values for each treatment were tested by Student's *t*-test (Zar, 1974). In the 100 ppm treatment mean NFL was significantly less than mean OFL ($P < 0.01$). There was no significant difference between mean NFL and OFL within each of the other treatments.

A similar examination was performed for endotheca length. Mean pre- and post-experiment endotheca length for each treatment is illustrated in Fig. 4. For each treatment, mean NEL was significantly lower than mean OEL (Student's *t*-test, $P < 0.01$). The endotheca bases of corallites in each treatment grew higher than the septa grew linearly, thus shortening the length of all corallites relative to their pre-experiment values. In order to assess if corallites within each treatment changed proportionately, new or post-experiment endotheca length was normalized to the length of the old endotheca by the ratio: NEL/OEL for all corallites. Mean values per treatment (see Table 1) are plotted in Fig. 5. Average values of NEL/OEL for corallites in the control, 1- and 10-ppm treatments were similar while the mean of corallites within the 100-ppm treatment was relatively elevated. This is explained by the small endotheca base increase (EBI) relative to septa increase of corallites in the 100-ppm treatment (discussed below).

Parameters of Upward Growth

Parameters which characterize the upward growth of corallites are the linear increase of the septa (SI) and columella (CI) as well as the upward rise or increase of the endotheca base (EBI) over the course of the experiment. These (and their ratio to OEL) are included in Table 2 and illustrated in Fig. 6. ANOVA and SNK testing for differences between treatment means for each of the normalized pa-

Table 2. *Montastrea annularis*. The effect of concentration of drilling mud on corallite shape and growth parameters of *M. annularis*. The mean, SD, and *n* are given

Control				1 ppm $n=20$		10 ppm $n=20$		100 ppm $n=20$	
	X̄ mm	SD	*n*	X̄ mm	SD	X̄ mm	SD	X̄ mm	SD
NFL	0.92	0.21	17	0.90	0.20	1.09	0.21	0.89	0.17
OFL	0.98	0.24	17	1.04	0.20	1.03	0.26	1.11	0.20
NEL	3.16	0.22	11	3.16	0.34	3.69	0.52	3.67	0.34
OEL	3.79	0.29	11	3.78	0.72	4.35	0.45	4.01	0.34
SI	0.75	0.18	17	0.55	0.16	0.96	0.23	0.36	0.11
CI	0.85	0.22	17	0.68	0.26	0.89	0.20	0.58	0.11
EBI	1.41	0.37	11	1.22	0.56	1.61	0.45	0.69	0.16
	X̄	SD	*n*	X̄	SD	X̄	SD	X̄	SD
SI/OEL	0.21	0.31	11	0.15	0.04	0.22	0.06	0.09	0.03
CI/OEL	0.21	0.03	11	0.18	0.05	0.21	0.04	0.15	0.03
EBI/OEL	0.37	0.08	11	0.31	0.11	0.37	0.11	0.19	0.04
NEL/OEL	0.84	0.09	11	0.86	0.14	0.85	0.10	0.92	0.05

SI = septa increase; CI = columella increase; EBI = endotheca base increase; NFL = new fossa length; OFL = old fossa length; NEL = new endotheca length; OEL = old endotheca length; *n* = the number of corallites measured for each parameter in each treatment (*n* was 20 for each in the 1-, 10-, and 100-ppm treatments, but varied as indicated for the control treatment)

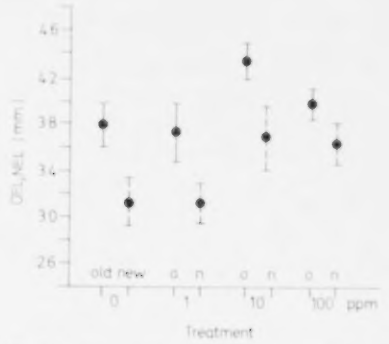

Fig. 4. *Montastrea annularis.* The effect of concentration of drilling mud on mean OEL (old endotheca length) and mean NEL (new endotheca length) of *M. annualris.* Error bar is the 95% confidence interval and is dashed for "new" values

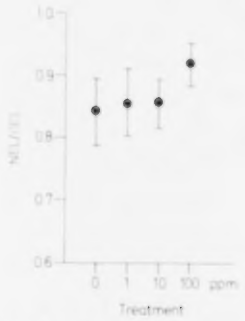

Fig. 5. *Montastrea annularis.* The effect of concentration of drilling mud on mean NEL/OEL (new endotheca length/old endotheca length) of *M. annularis.* The error bar is the 95% confidence interval

rameters showed that in all cases coral growth was significantly depressed in the 100-ppm treatment relative to the other treatments (with the exception that the 100-ppm mean CI/OEL was significantly less than the control and 10-ppm mean values but equivalent to the 1-ppm mean). In general, there were no consistent statistically significant differences between the control, 1- and 10-ppm means within each parameter grouping.

Discussion

Drill Mud Composition

The composition of the drill mud used in this experiment varied from week to week. This study does not allow for differentiation of effects between weeks of exposure. The concentrations of most components remained relatively stable with the exception of hydrocarbons (diesel) which comprised approximately 0.4% by weight of the mud during the fourth experimental week to the end of the experiment. Hydrocarbons in marine mud discharges are not uncommon in the United States (e.g. Pierce *et al.*, in press).

Effects of Staining

Alizarin red S has been used commonly to place "time line" markers of color in coral skeletons from which to evaluate new growth (e.g. Barnes, 1970, 1972; Glynn and Stewart, 1973; Lamberts, 1974; Buddemeier and Kinzie, 1975; Dustan, 1975; Houck *et al.*, 1977; Foster, 1979). Lamberts (1978) suggested that alizarin may be mildly toxic. It is possible that staining pre-treatment, shortly before drill mud exposure, placed an additional stress on all corals. The effect is expected to have been short relative to experimental length (Dodge *et al.*, unpublished data).

Upward Growth

Growth rate is a measure of health or viability of an invertebrate organism. Sekeletal extension or growth rate measures the ability of a coral to deposit its skeleton and is an index of this important process of the coral animal. Growth rate changes in corals occur in response to natural resuspension of bottom sediments (Dodge *et al.*, 1974), sedimentation and turbidity effects from dredging (Dodge and Vaisnys, 1977; Bak, 1978), latitudinal temperature changes (Weber and White, 1977), and depth changes (Baker and Weber, 1975).

This study demonstrates that *Montastrea annularis* chronically exposed for longer than six weeks to 100-ppm

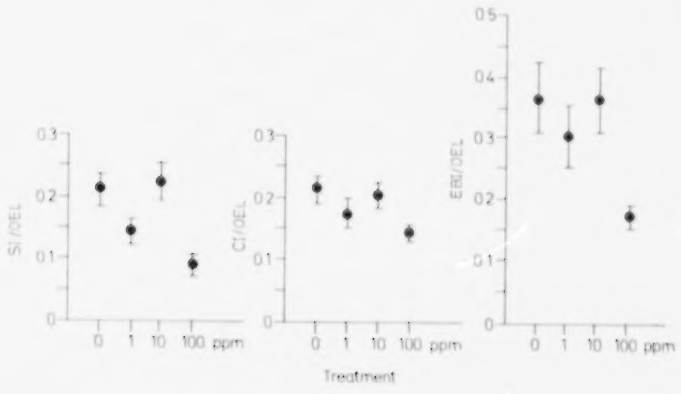

Fig. 6. *Montastrea annularis.* The effect of concentration of drilling mud on mean normalized upward growth parameters of *M. annularis.* The error bar is the 95% confidence interval. SI/OEL = septa increase/old endotheca length; CI/OEL = columella increase/old endotheca length; EBI/OEL = endotheca base increase/old endotheca length

drill mud had significantly depressed linear growth rate and increased mortality. Because of mortality in the 100-ppm treatment, these corals grew over a period of time effectively 6% less than that for the corals of the other treatments. The time difference was short and probably insufficient to bias results. The growth results do not indicate lowered growth from either 10- or 1-ppm exposure over the experimental period.

Szmant-Froelich *et al.* (in press) periodically measured calcification rates (by the alkalinity method) of all corals in this experiment. Calcification rates of corals exposed to 100-ppm drilling mud decreased by 53% after four weeks and by 84% after six weeks. Those corals within the control, 1 and 10 ppm, did not. Hudson and Robbin (1980) found that colonies of *Montastrea annularis* exposed to high concentrations of drilling mud (slurry applications) over a 10-h period had decreased growth rate over a subsequent six-month period.

Shape

The shape of corallites of *Montastrea annularis* varies within and between individual coral colonies. Nevertheless, corallite morphology can be quantified and is related to environmental factors (Foster, 1979). Specific morphologies within a species are probably best phenotypic adaptations to particular environments within genotypic limitations. Relief of corallite structures promotes sediment rejection by increasing the surface area of the calice and thus the polyp distension potential. In addition, high relief alone aids sediment removal by promoting greater passive flow of sediment off the coral surface. Hubbard and Pocock (1972) related morphology of the coral polyp skeleton to the ability to reject sediment. *M. annularis* is an efficient sediment-rejector with high calical relief. Lasker (1980) found that nocturnal morphs of *M. cavernosa* with taller polyps (and more calical relief) are more efficient sediment rejectors.

Fossa length is an index of vertical relief of the corallite. Any effect which decreases the calical relief of the skeleton would also presumably decrease the ability for sediment rejection. This might, at least temporarily, put a coral at a disadvantage for removing sediment, even after the event which had promoted the changed skeletal morphology had ceased. Corallites of corals for this study showed a decreased fossa in the 100-ppm drill mud treatment. This suggests possibly impaired sediment rejection capability for a period of time after 100-ppm drill mud exposure which might lower the capacity for survival even after the drill mud stress had ended.

Alternatively, Foster (1980) has shown that Jamaican *Montastrea annularis* individuals collected from a moderate sedimentation environment have greater fossa length than individuals from sites of either high or low sedimentation. Many factors influence the sediment rejection capability of corals (e.g. overall colony shape and size, tissue volume, etc.) and may be equally or more important than fossa length and calical relief.

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